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Vineyards in transition: A global assessment of the adaptation needs of grape producing regions under climate change

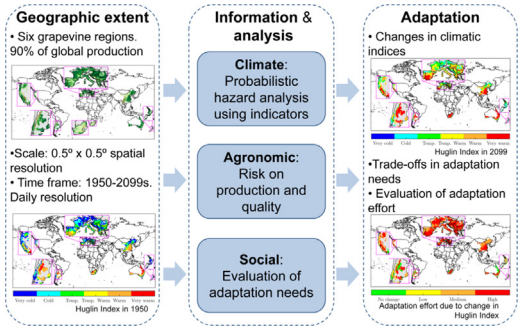
David Santillán [a,*], Ana Iglesias [b], Isabelle La Jeunesse [c], Luis Garrote [a], Vicente Sotes [d]

[a] Departamento de Ingeniería Civil: Hidráulica, Energía y Medio Ambiente, Universidad Politécnica de Madrid (UPM), Spain
[b] Departmento de Economía Agraria, Estadística y Gestión de Empresas, Universidad Politécnica de Madrid (UPM), Spain
[c] Laboratory CNRS 7324 Citeres, University of Tours, France
[d] Departmento de Producción Agraria, Universidad Politécnica de Madrid (UPM), Spain

HIGHLIGHTS

- Climate change will transform grapevine production and policy.
- Thermal suitability of grapevine may be greatly affected in China and the Mediterranean region.
- The possibility of quality wines is not altered within the regions with suitability.
- A lack of water to maintain current levels of production is detected in all regions.
- The Mediterranean region requires the largest adaptation efforts.

GRAPHICAL ABSTRACT


Geographic extent
• Six grapevine regions. 90% of global production
•Scale: 0.5° x 0.5° spatial resolution
• Time frame: 1950-2099s. Daily resolution
Huglin Index in 1950
Information & analysis
Climate: Probabilistic hazard analysis using indicators
Agronomic: Risk on production and quality
Social: Evaluation of adaptation needs
Adaptation
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ABSTRACT

This paper suggests how climate change may transform vineyards. We consider changes in agro-climatic indicators derived from climatic variables as drivers for adaptation needs. We use two climate scenarios, GCM GFL-ESM2M and HadGEM2-ES, with 0.5° spatial resolution and daily time step forced by two emission scenarios, RCP2.6 and 6.0, to estimate the transition of potential vineyards in the major grape production world areas by the late 21st century. We present and discuss changes in three impact indicators – one drought indicator and two temperature ones – aimed at exploring the benefits of transition-based policies. The drought indicator provides insights to prepare adaptation for extreme events in probabilistic terms. The temperature indicators offer information on the transition towards suitable zones of production. Future projections suggest a lack of water to maintain current levels of production in all regions of the world. Furthermore, thermal suitability of grapevine may be greatly affected in China and the Mediterranean region. Nevertheless, the possibility of quality wines is not altered within the regions with adequate suitability. Lastly, a portfolio of strategies to adapt to the future climate is presented.

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1. Introduction

Promoting the adoption of adaptation measures in grapevine production regions is a pressing policy concern. Grape and wine production offers many economic, social and environmental benefits, through trade, rural income, employment, and tourism, among others.

* Corresponding author.
E-mail address: david.santillan@upm.es (D. Santillán).

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Furthermore, carbon-dioxide emissions from vineyards are lower than alternative crops, with less water consumption.

Moreover, wine and its consumption is a cultural heritage in all Europe. This agricultural activity also helps to promote adaptation plans. In most cases, plans are designed by the large variety of stakeholders involved in the sector, from industry to farmers (Belletti et al., 2017). Up to now, however, a comparative study of the global adaptation strategies (e.g. irrigation, rootstock or biotechnological improvement of plants) in the sector is rather limited (Sacchelli et al., 2016). Given that climate change risks may gain importance and consideration in future planning decisions, it is important that stakeholders consider a range of possible transitions, which could even rely on normative development. From an economic point of view, efforts to implement adaptation action may encompass additional costs to the sector. However, these new expenses need to be compared to the possible reduction of incomes caused by inaction against future climate. Policy and financial support can serve as additional financial incentives for the private sector.

From a policy perspective, previous research highlights the necessity of tailoring support for climate change adaptation policies including elements accounting both for the greater upfront support for transforming agronomic choices (e.g., soil management to increase soil organic carbon), and the transformation of current normative (e.g., choices of grape varieties in some regions) (Belletti et al., 2017).

For a given soil-climate combination, each grape variety has well defined thermal requirements in order to complete the vegetative cycle and overcome heat and water stress. For instance, grape varieties "Grenache" and "Merlot" are cultivated in the Mediterranean region, where great shifts in bioclimatic indices are expected to occur (Moriondo et al., 2013). Whereas the variety "Grenache" is extremely well adapted to water scarcity, the "Merlot" demands higher amounts of water (Jones et al., 2012). Excess exposure to heat, causes leaf burning due to direct heat and subsequent dryness of leafs. Sensitivity to heat and water stress can be modified, to some extent, by pruning methods. Pruning methods that maintain large vegetation growth, decrease heat stress since grapes are kept shaded; however, an excess of vegetation increases water needs. Traditional pruning systems that maintain vegetation close to the terrain, are efficient in dry areas, since water needs are much lower because leafs are shaded. However, these systems are only economically sustainable in some areas, since operation and maintenance costs are higher due to the demanding labour. Excessive water stress can also be compensated through irrigation. Irrigation enables the possibility to control the water available to the plant to obtain the optimum water stress required for premium quality. However, climate projections suggest a global reduction of water availability in most grape producing areas. Water scarcity together the allocation of water supply to uses with higher priority than agriculture may lead to unfavourable contexts. These complex climate-agronomic-social interactions define the limits and transitions towards adaptation to future climate at the regional level.

Viticulture is a complex sector that integrates production quantity, quality, water resources, and also the wine production industry. The impacts of climate change have been widely evaluated. In recent years it is clear that climate change has already impacted the sector: the ripening date has advanced unequivocally in many areas, and stakeholders are seriously considering the sustainability of the current model of production. The debate on adaptation needs has moved from science to practitioners, demanding more information on impacts. We recognise the valuable contributions of the previous knowledge of the risk of climate change in grapevine (Table 1). We build on previous knowledge to define the goals of this study: a global assessment, with common datasets, assumptions and analytical methods to evaluate risks and opportunities; a novel probabilistic approach that evaluates the risk of drought; a systematic combination of indices that characterise quality and quantity; and an evaluation of the adaptation needs with common assumptions.

Table 1
Climate change impacts on vinegrapes, regional scope and representative studies.

Main impact of climate change	Scope	Representative studies
Descriptive evaluation of several aspects	Comprehensive overview	Schultz and Jones (2010); Jones et al. (2012); Fraga et al. (2012); Ashenfelter and Storchmann (2016); Cook and Wolkovich (2016); Schultz (2016)
Changes in optimal growing areas	Global analysis	Daux et al. (2012); Hannah et al. (2013); de Cortázar-Atauri et al. (2010, 2017); van Leeuwen et al. (2013); Wolkovich et al. (2018)
Combination of several indicators	Regional analysis	Schultz (2000); McInnes et al. (2003); Seguin and de Cortazar (2005); Duchêne et al. (2010); Tomasi et al. (2011); Trnka et al. (2011); Moriondo et al. (2011, 2013); Camps and Ramos (2012); Jones and Alves (2012); Ferrise et al. (2016); Resco et al. (2016); Lazoglou et al. (2017)
Drought analysis	Regional analysis	Cook and Wolkovich (2016); Gambetta (2016)
Adaptation of management	Crop management	Jackson and Lombard (1993); Webb et al. (2012); Duchêne et al. (2014); Mosedale et al. (2016)
Quality	Economic	Oczkowski (2016); Mozell and Thach (2014)
	Agronomic	Parker et al. (2011); Leibar et al. (2015)
	Oenology	Tate (2001); Mori et al. (2007); Webb et al. (2008); de Oruña (2010); Mira de Orduna (2010); Bock et al. (2013); Jones et al. (2005, 2015)

This study aims to estimate how climate change may transform global grape producing regions, incorporating novel features which are of interest for developing policies that drive adaptation strategies. We assess climate risks to grape production, the agronomic implications, and elucidate the adaptation needs in six regions covering about 90% of the global grapevine production, over the time period 1950 to 2100.

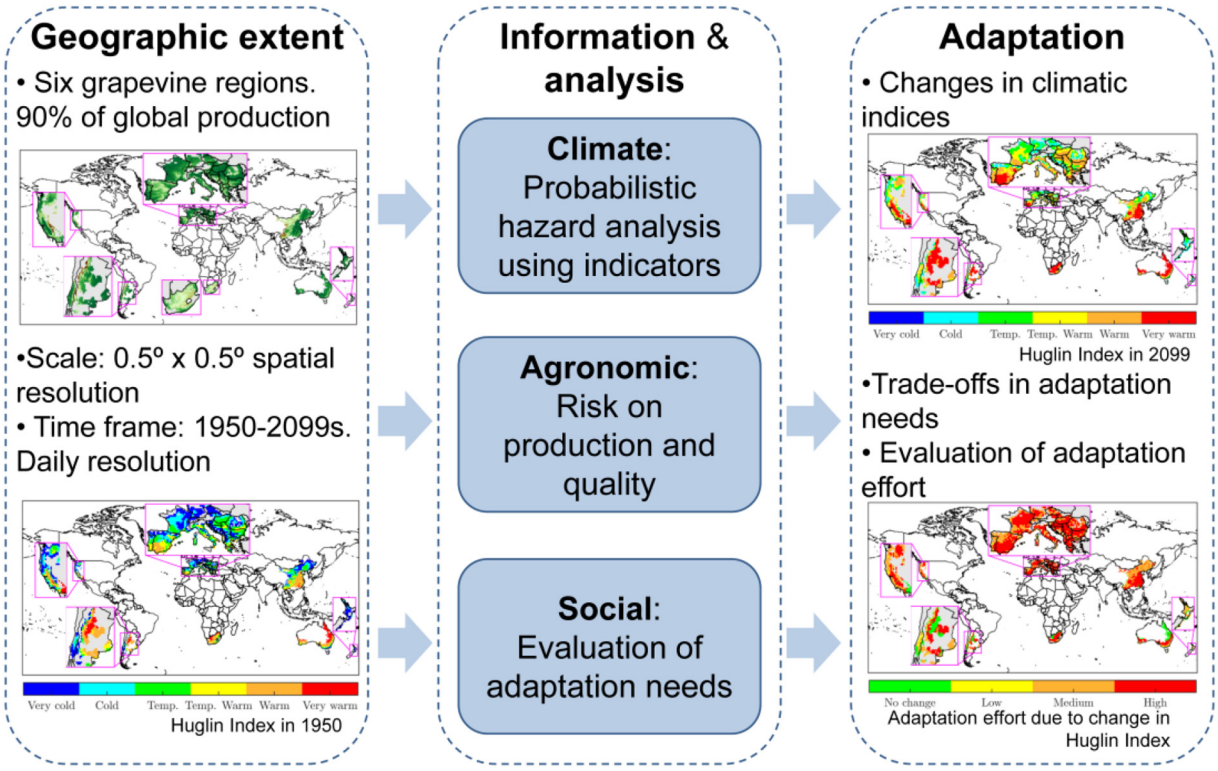
2. Methods and data

2.1. Framework

Our approach evaluates needs for transition in the main global grapevine production regions, by estimating how climate influences the agronomic performance of the crop and what adaptation choices are available in each region (Fig. 1). Climate risk is defined by changes in the Huglin Index (Huglin, 1978), Cool Night and Standardized Precipitation Evaporation (SPE) Indices. The shift in the indices provides information about the adaption needs. In the following subsections, we describe the datasets used in this study, the assessment of the change in indices, and the definition of the adaptation needs. Many of the components and inter-relationships outlined in this study have been analyzed elsewhere, such as the application of the main agro-climatic indices with varied aims and datasets used across different areas (Trnka et al., 2011; Jones et al., 2009, 2012). This study highlights that climate change adaptation needs depend on variables that are intricately interconnected, and that the complex picture varies across regions. It recognizes the potential for transforming grape growing regions and defines the effort needed at the regional level.

2.2. Data

Our study covers the main producing grapevine regions of the world. We identify the main grape producing areas using harvested area and yield for grape crops available in the EarthStat worldwide database at $0.5° \times 0.5°$ spatial resolution (Monfreda et al., 2008). For the purpose of this study, we cluster them into six major regions (Fig. 2): the west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No change Low Medium High
Adaptation effort due to change in Huglin Index

Fig. 1. Graphical abstract of the study framework.

coast of North America, Europe, China, South America, South Africa and Oceania, which includes Australia and New Zealand.

Historical and future climate scenarios are provided by the Inter-Sectoral Impact Model Intercomparison Project phase 2b (ISIMIP2b) (Frieler et al., 2016). Data are available at worldwide 0.5° × 0.5° spatial resolution and daily time step. Data are bias-corrected through a statistical method based on the transfer function approach applied in the Water Model Intercomparison Project (Water-MIP) (Hempel et al., 2013; Frieler et al., 2016). The method adjusts monthly means and daily variability of simulated climate data to observations from the compiled reference dataset EWEMBI (Frieler et al., 2016; Lange, 2018). Bias-corrected data are available from four general circulation model (GCM) outputs: IPSL-CM5A-LR, GFDL-ESM2M, MIROC5, and HadGEM2-ES models, driven by the Representative Concentration Pathways (RCP) RCP2.6, RCP4.5, RCP6.0, and RCP8.5.

We adopt climate scenarios constructed from the general circulation model outputs GFDL-ESM2M and HadGEM2-ES. Given a RCP, the climatic projection provided by these two models covers the minimum and maximum future temperature changes (Warszawski et al., 2014). In most of the annual climatic projections up to year 2100, the maximum temperature rise is provided by the HadGEM2-ES model, whereas the minimum increment by the GFDL-ESM2M model. Our selection tries to cover the whole future climate range variation, taking into consideration uncertainties.

Regarding the concentration pathways, climatic projection with the four RCP adopted by the Intergovernmental Panel on Climate Change for its fifth Assessment Report are available. The RCP2.6 is a mitigation scenario with a very low forcing level. It provides an estimate of future climate even if greenhouse gas emissions are considerably reduced with drastic policy interventions (van Vuuren et al., 2011). The RCPs 4.5 and 6.0 are medium stabilisation scenarios, involving the reduction of greenhouse gas emission with modest and important policy interventions, respectively (Masui et al., 2011). The RCP8.5 is a high emission scenario with no climate mitigation policies (Riahi et al., 2011). We have selected pathways RCP2.6 and 6.0 for our study, in order to cover the range from high to modest climate mitigation policies.

2.3. Agro-climatic indices

We estimate future impact on wine regions using a combination of bioclimatic indices, which has been recognized as the most adequate approach by previous studies (Tonietto and Carbonneau, 2004; Moriondo et al., 2013). The most representative indices adopted in previous studies are the Huglin Index, the Cool Night Index and a dryness index. We select as dryness indicator the Standardized Precipitation-Evaporation (SPE) index (Beguería et al., 2010).

The Huglin Index is a thermal indicator that measures the thermal suitability for wine production at a given location (Huglin, 1978). This indicator characterizes the suitability of viticulture in general and particular grapevine crops at a given location. The Cool Night Index is a thermal indicator that accounts for the minimum night temperature during the ripening period and provides information about the quality of the wine, in terms of aroma and color of grapes and wine (Kliewer and Torres, 1972; Kliewer, 1973; Tonietto and Carbonneau, 2004). The SPE Index is a drought indicator based on the precipitation and the potential evapotranspiration. It allows comparison of drought severity through time and space, since it can be assessed over a wide range of climates (Beguería et al., 2010; Vicente-Serrano et al., 2010), and provides insights to prepare for extreme drought events in probabilistic terms. The SPE Index is important since water stress has effects on the grape ripening and wine quality (Seguin, 1983; Jackson and Lombard, 1993; Carbonneau, 1998). The description of the climatic indicators, as well as the mathematical formulation, category names, and range of values that define the various agro-climatic classes are included in Table 2.

We compute the evolution of the indices at every cell of the spatial grid for a given climatic projection in four steps. An illustration of our approach is included in Fig. 3, where the methodology is applied for computing the shift in the Huglin Index in one cell located in the centre

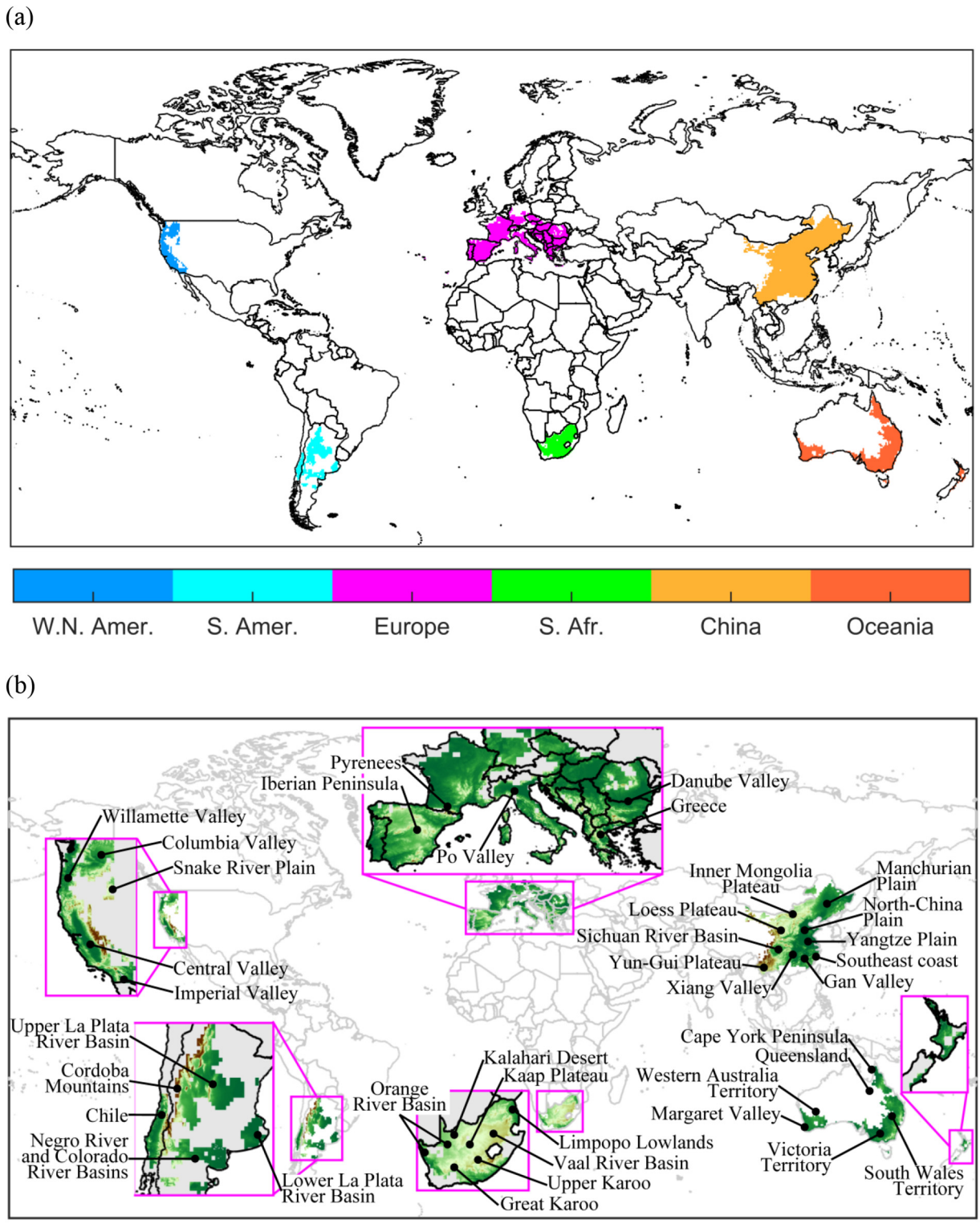


Fig. 2. Grapevine production regions. (a) Main regions of the world: West-North America, South America, Europe, South Africa, China and Oceania. (b) Map with locations.

of France. First, we compute the indices at every grid cells according to the mathematical expressions listed in Table 2 using the climatic projections. Afterward, we detect trends in the evolution of the indices with the Mann-Kendall (MK) test. The MK test is a robust non-parametric test commonly used for monotonic trend detection. The test is particularly suitable for non-normal distributed and serially correlated data series (Kundzewicz and Robson, 2004). It is robust to outliers and does not require any assumption related to the probabilistic distribution of the series (Hamed and Rao, 1998). The MK test statistic, S, has the form:

$$S = \sum_{i=1}^{T-1} \sum_{j=i+1}^{T} \mathrm{sgn}(Y_j - Y_i), \tag{1}$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1 \text{ for } \theta > 0 \\ 0 \text{ for } \theta = 0, \\ -1 \text{ for } \theta < 0 \end{cases} \tag{2}$$

Table 2
Description of the selected climatic indicators: the Huglin Index, the Cool Night Index and the Standardized Precipitation-Evaporation Index. The information in the table includes the mathematical expression, category names, and range of values that define the various agro-climatic classes.

Index description	Expression	Category name	Range of values
Huglin Index (HI)	$HI = \sum_{i=Dini}^{Dend} \frac{(T_i - 10) + (T_{max,i} - 10)}{2} d$ where Dini is the starting date — 1st April in the Northern Hemisphere and 1st October in Southern, Dend is the ending date — 30 September in the Northern and 31st March in the Southern, T_i is the average daily temperature in °C, $T_{max,\,i}$ is the maximum daily temperature in °C, and d is a coefficient that depends on the day length.	Very warm Warm Temperate warm Temperate Cool Very cool	HI > 3000 2400 < HI ≤ 3000 2100 < HI ≤ 2400 1800 < HI ≤ 2100 1500 < HI ≤ 1800 HI ≤ 1500
Cool Night Index (CNI)	In the Northern Hemisphere: CNI = minimum air temperature in the month of September In the Southern Hemisphere: CNI = minimum air temperature in the month of March	Very cool nights Cool nights Temperate nights Warm nights	CNI ≤ 12 12 < CNI ≤ 14 14 < CNI ≤ 18 CNI > 18
Standardized Precipitation-Evaporation Index (SPEI)	SPEI is the standardized value of the probability distribution function of the monthly difference (D_i) series, defined as: $D_i = P_i - PET_i$ where P_i is the monthly precipitation, and PET_i is the monthly potential evapotranspiration. We compute PET with Thornthwaite equation (Thornthwaite, 1948), and D_i is aggregated at three months and assumed to follow a log-logistic distribution (Vicente-Serrano et al., 2010) In the Northern Hemisphere: i = September In the Southern Hemisphere: i = March	Very dry Dry Moderately dry Sub-humid Humid Very humid	SPEI ≤ −1.5 −1.5 < SPEI ≤ −1.0 −1.0 < SPEI ≤ 0.0 0.0 < SPEI ≤ 1.0 1.0 < SPEI ≤ 1.5 SPEI > 1.5

where Y_i and Y_j are the sequential input data values and T is the record-length. We detect significant trends for p-values with a significance level of <5%. In order to reduce the influence of serial correlation on the MK results, the test is applied on the time series Y where the serial correlation between data is reduced using the trend free pre-whitening procedure (Yue and Wang, 2002).

In the third step, we estimate the magnitude of the significant trends by Sen's slope (Sen, 1968):

$$\beta = \text{median}\left(\frac{Y_j - Y_i}{j - i}\right) \forall i < j. \quad (3)$$

Lastly, we determine the value of the indices in 1950 and 2099 using the adjusted linear trend computed with Sens's slope — Eq. (3).

Fig. 3 illustrates the methodology. First we estimate the magnitude of the index with a given climatic projection in all the cells of the grid every year from 1950 to 2099. As for instance, we plot the Huglin Index in 1950 in Fig. 3a. We also plot the evolution of the index from 1950 to 2099 in the cell in red of Fig. 3a (located in the centre of France) in panel (b). The blue points are the values of the Huglin Index, and the red line is the adjusted linear regression to the blue points. The linear trend allows us to estimate robust values of the indices in 1950, as well as in 2099. Using the linear fit, we also estimate changes in the indices as the difference between the values in 2099 and 1950. For the Huglin Index, we denoted the change with ΔHI.

2.4. Adaptation needs

The adaptation efforts as consequence of changes in the climatic indices are calculated as proportional to the magnitude of the change at each cell, based on Tonietto and Carbonneau (2004). We identify the climatic scenarios that involve the lower and higher changes in indices. The low impact scenario corresponds to the projections with the lowest temperature increment and rainfall decrease, which is expected to

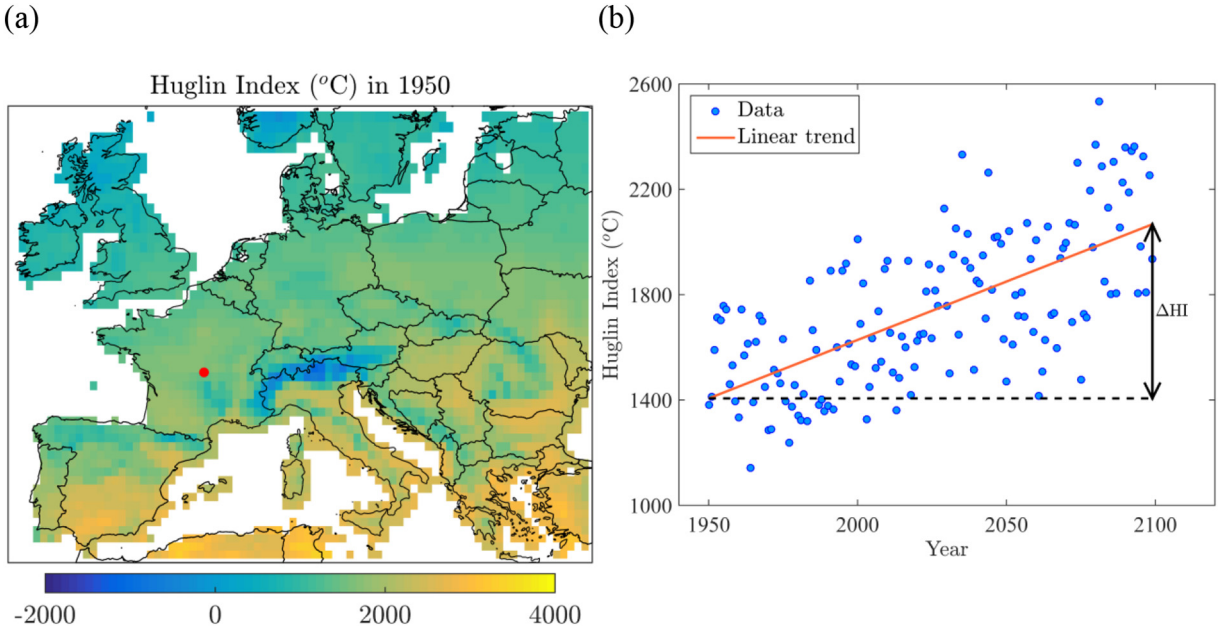


Fig. 3. Illustration of the methodology. (a) Plot of the Huglin Index in 1950.The evolution of the Huglin Index in the red point of panel (a) is depicted with blue points in panel (b). In the same plot, the red line is the fitted linear trend to the values of the Huglin Index.

produce the lowest changes in the agro-climatic indicators. In the same way, the high impact scenario is the projection with the highest increase in temperature and decrease in rainfall. It is expected to generate the highest changes in the indices. Afterwards, we use the qualitative index change (difference between the values in 2099 and 1950) at every grid cell as a measure of the adaptation efforts. Future adaptation needs are categorized into low, medium or high (Table 3), based on Tonietto and Carbonneau (2004).

2.5. Limitations and sources of uncertainty

The main limitations of the analysis derive from the imperfect data (e.g. limited climate projections), limitation of the selected agro-climatic indices to represent complex reality (e.g. grapevine quality and quantity), and the assumptions about the future adaptation of the production systems (e.g., changes in current varieties and technology, among others). These limitations are the cause of uncertain results. A main source of uncertainty is derived from the climate scenarios, especially in the selection of individual projections. The assumptions used to derive climate change scenarios is a great challenge that is constantly being addressed (Moss et al., 2010). Some climate change impact studies use multiple projections, and analyze their ensemble behaviours that characterise future climate (Challinor et al., 2014). When the analysis focuses on adaptation, the critical adaptation effort may be well characterised by a detailed evaluation under individual projections (e.g., Vrzel et al., 2019; Jin et al., 2018a, 2018b; Pesce et al., 2018). The strength of our study is the use of climate projections consistently shared in numerous impact studies, carried out under the ISIMIP2b project. This project provides projections for four GCMs, which would be a very small number to build an ensemble. We have selected two of them, the maximum and minimum ones, in order to cover the range of future climate variation and take uncertainties into consideration. Our approach to analyze two scenarios that cover the full range of temperature projections, supports the aims of the study to characterise the adaptation needs in order to inform policy change. The uncertainty of the agro-climate indices used is derived from the limitations of simple values to represent complex agro-ecosystem dynamics. However, the strength our results is derived from the recognition that this approach is very widely used (Tonietto and Carbonneau, 2004) and that these indices are consistent with empirical data that define the reference period for our study. Grapevine clones and management practices evolve continuously and have advanced enormously in relation to adaptation to local climate and production conditions; nevertheless, the main features of crops that determine response to temperature variations (phenology) are quite stable. In summary, uncertainty can never be estimated in probabilistic terms since it reflects imperfect knowledge: here uncertainty is derived from the climate scenarios, the agro-climatic indices and the assumptions about the characterisation of the adaptation needs based on the projected changes of agro-climatic indices.

3. Results and discussion

In the following subsections, we describe the evolution of the indices in the six wine producing regions, the probabilistic projections of the changes, as well as the expected adaptation needs.

3.1. Risk analysis using agro-climatic indicators

We evaluate the consequences of climate change by estimating changes in bioclimatic indices for the climate in 1950 and the projected climate conditions in 2099, both computed through the regression method described in the methodology section. The Huglin Index, the Cool Night Index, and the SPE Index present major changes in most areas of the world. The results of the climate models indicate that potential grapevine production areas could evolve into more unfavourable climatic conditions (Fig. 4).

The Huglin Index may increase throughout the study regions (Fig. 4a–b). For southern regions of Europe, USA, and China, and northern regions of Argentina and South Africa the expected increase of the index up to warm or very warm values may indicate a potential risk of heat stress and over-ripening. The consequence of this increment is lower-quality wines, and may require growing new warmer climate grape varieties. In northern areas of Europe, USA, China, and New Zeeland, as well as southern regions of Chile and eastern part of South Africa the index is also expected to increase up to temperate or temperate warm category classes, enabling a vineyard expansion. The current frost damage may decrease, but not disappear, and the temperature rise may increase the suitability of vineyards to more grape varieties.

The Cool Night Index is projected to increase in most areas of southern Europe and China and northern New Zealand (Fig. 4c–d), indicating potential quality losses as the grape varieties ripen earlier. The rise in night temperature may involve grapevines with lower aroma content and lighter color. Nevertheless, current areas too cold for adequate ripening, as for instance the north areas of USA or New Zealand, may be benefited from the increase in night temperatures.

Table 3
Matrix to evaluate future adaptation efforts due to the shift in the Huglin Index, Cool Night Index and SPE Index.

Adaptation effort						
Index value in 1950	Index value in 2099					
Huglin Index	Very warm	Warm	Temperate warm	Temperate	Cool	Very cool
Very warm	No change					
Warm	High	No change				
Temperate warm	High	Medium	No change			
Temperate	High	Medium	Low	No change		
Cool	High	Medium	Low	Low	No change	
Very cool	High	High	Medium	Medium	No effort	No change
Cool Night Index	Warm	Temperate	Cool	Very cool		
Warm	No change					
Temperate	High	No change				
Cool	High	Medium	No change			
Very cool	High	Medium	Low	No change		
SPE Index	Very dry	Dry	Moderately dry	Sub-humid	Humid	Very humid
Very dry	No change					
Dry	High	No change				
Moderately dry	High	Medium	No change			
Sub-humid	High	Medium	Low	No change		
Humid	High	Medium	Low	Low	No change	
Very humid	High	High	Medium	Low	No effort	No change

The evolution of the SPE Index (Fig. 4e–f) projects potential higher deficit of water during the growing season in most areas of the world. The projection is especially dramatic in Europe and USA, where irrigation seems to be mandatory. In the remaining regions, the trends also lead to deficits. Nevertheless, the reduction in humidity in some areas of South America or China could be beneficial for ripening and the reduction of diseases, but irrigation would be needed for preventing frequent water stress.

3.2. Probabilistic projections

We study the probabilistic changes in the three indices when significant trends are detected for the six regions and the four projections (Fig. 5). The boxplots provide us an opportunity for elucidating the variability of the indices in every region, model and forcing. We draw one boxplot for each index, region, and climatic projection.

The absolute medians of the changes in the indices computed with the forcing RCP6.0 are higher than the values with RCP2.6 for all the indices and regions. Similarly, projections with the HadGEM2-ES model provide higher medians than the ones computed with the GFDL-ESM2M model. Regarding the variability in predictions – the interquartile range – these are higher for the projections with the RCP6.0 forcing than with the RCP2.6 one, and in general higher for the projections with the HadGEM2-ES model than with the GFDL-ESM2M one.

The Huglin Index (Fig. 5a) presents high variability for all regions with a strong dependence on the climate model and forcing. The regions with the greatest changes are concentrated in Europe and North America, although a great variability between models and forcing exits. The Cool Night Index (Fig. 5b) also shows high variability in projections for all regions. The region with the greatest changes is Europe for all models and forcing, except for model GFDL-ESM2M with forcing RCP2.6 that is China. The SPE Index during the growing season (Fig. 5c) presents greatly variability, as for instance the low value in Europe and the high ones in China. The greatest changes for those areas with significant trends are concentrated in South Africa, but the region with most percentage of areas with significant trends is Europe.

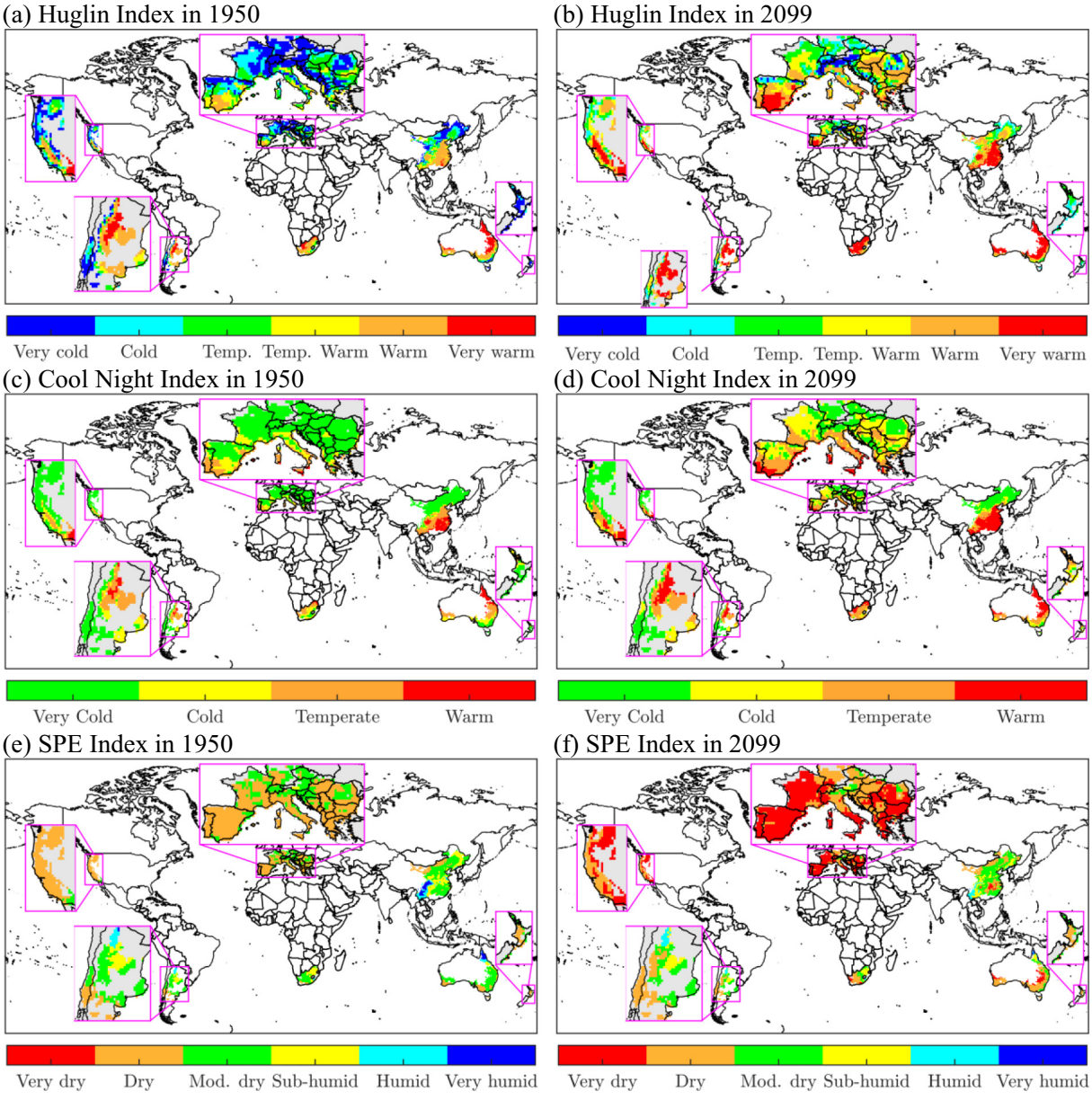


Fig. 4. Robust magnitude of the climatic indices for the climate in 1950 and the climate conditions in 2099, both constructed from outputs of simulations with the GCM GFDL-ESM2M, input ISIMIP2 Phase b, and driven by the RCP6 emission scenario. The robust magnitude of the indices is estimated through the adjusted linear regression to the computed value of the indices with the outputs of the corresponding GCM simulation.

3.3. Dependency between indices

We study the dependency between the indices for each climate projection and region of the world by plotting one index against another one (Fig. 6). The plots give us the opportunity to analyze the type of dependency between indices and qualitatively assess changes in every region for every climatic projection. In the following paragraphs, we refer to the worst-case scenario as the projection with the highest changes in indices.

The Huglin Index and the Cool Night Index present a linear positive dependency in all regions (Fig. 6a). Since both indices are thermal indicators and temperatures are projected to increase, the positive dependence is expected. The higher changes for both indices are concentrated in Europe, especially in the Mediterranean region where the Huglin Index and the Cool Night index could respectively increase up to 1500 °C and 7 °C for the worst-case scenario. Lower changes in the Huglin Index are detected in China and North America, where the rise is up to 1200 °C, but the Cool Night Index is expected to increase by the same quantity as in Europe. Lower increments are expected to occur in the Southern Hemisphere, where the worst-case scenario projects increments of the Huglin Index up to accumulated 900 °C per year in South America and Oceania, and accumulated 1200 °C per year in South Africa. The Cool Night Index could rise up to 6 °C in South America and South Africa, and 5 °C in Oceania. As we point out in the previous section, a great variability between model projections and forcing is obtained. For the same forcing, the expected change could increase up to double, depending on the model.

The dependency between the Cool Night Index and the SPE Index alternates among regions (Fig. 6b). Whereas a linear relationship between both variables seems to emerge in North America, an exponential dependency appears in Europe, and no clear dependency arises in China or Oceania. We detect trends towards lower values of the SPE Index in most areas of all regions, and the water deficits appear to be higher with the rise of the Cool Night Index. The SPE Index is projected to decrease up to 2.5 units in Europe, China and some areas of South America, and up to 1.5 units in the remaining regions for the worst-case scenario. However, some areas of China and South America are expected to become more humid due to the expected increase in rainfall.

The Huglin Index and the SPE Index present a linear dependency in Europe, North America, South Africa, and Oceania, but no clear relationship is presented in China or South America (Fig. 6c). The discordance in these two regions may arise from the fact that although the evapotranspiration is expected to increase due to the rise in future temperatures, the rainfall may increase in some areas of China and South America, and the total balance results in positive shifts of the SPE Index. In the remaining areas of the world, a potential deficit of water is expected to occur. The SPE Index seems to decrease with the increment in the Huglin Index, resulting in a potential deficit of water whose severity may be higher with the rise of the latter index. This pattern is partially expected by the increase of evapotranspiration due to the shift in temperatures.

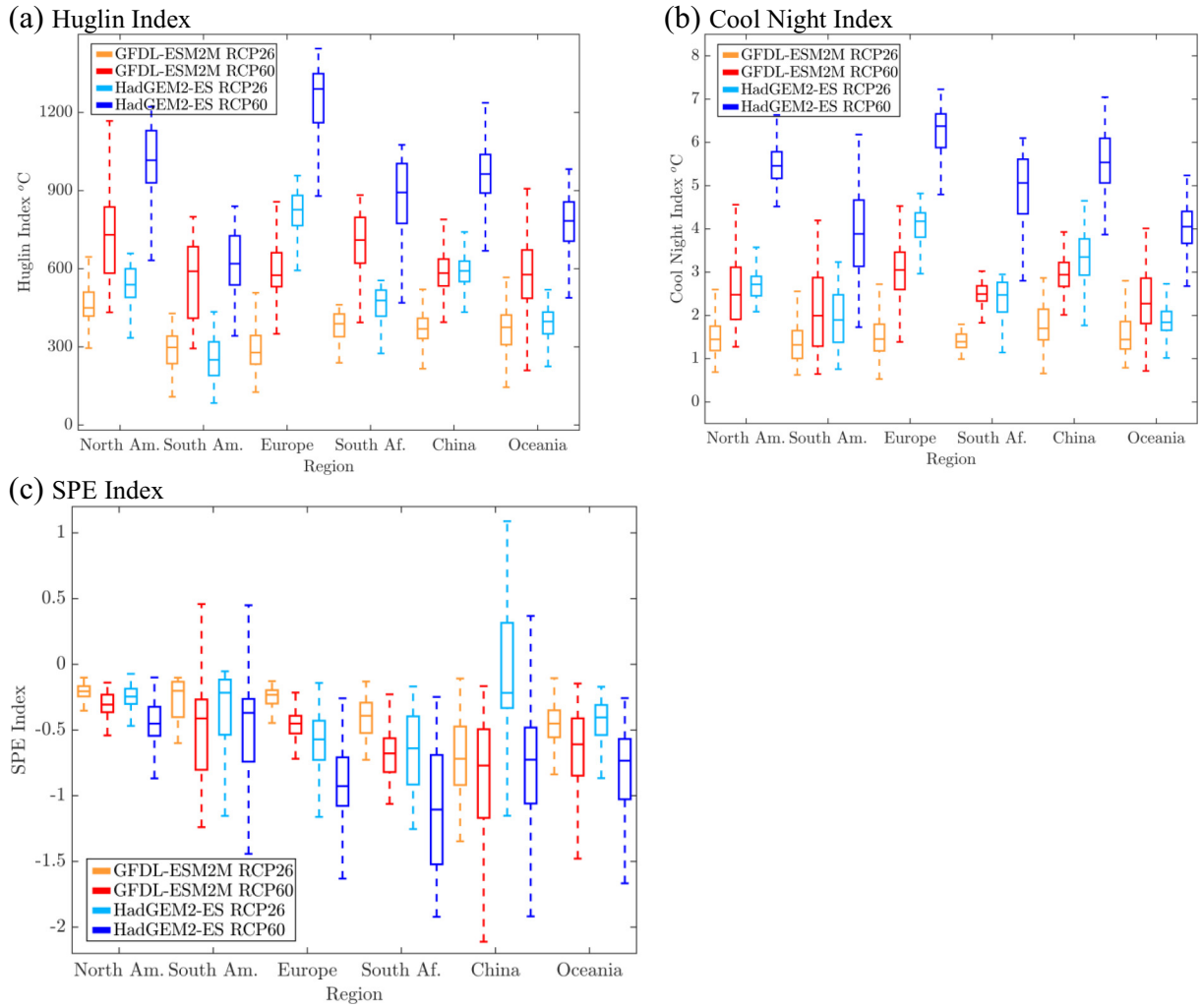
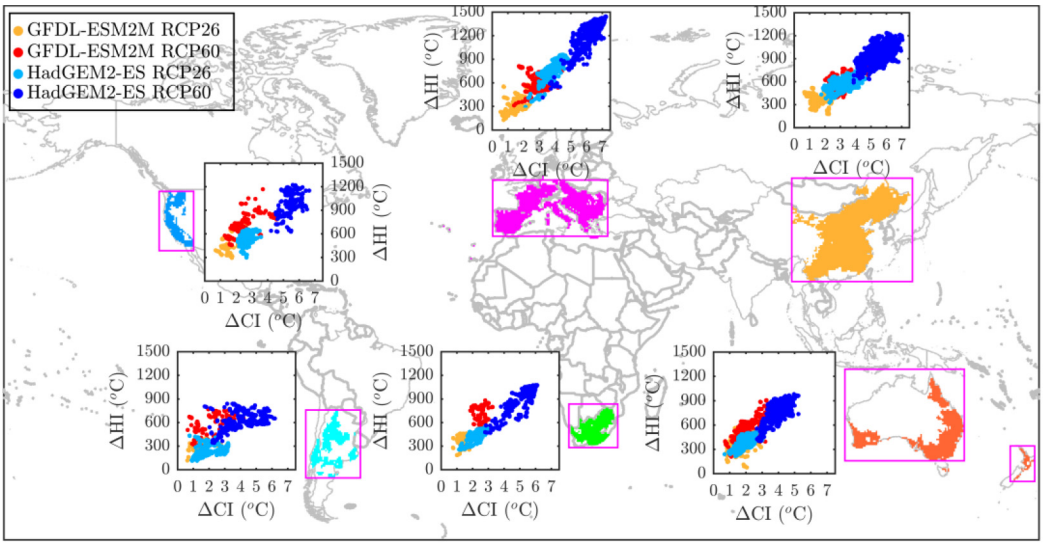
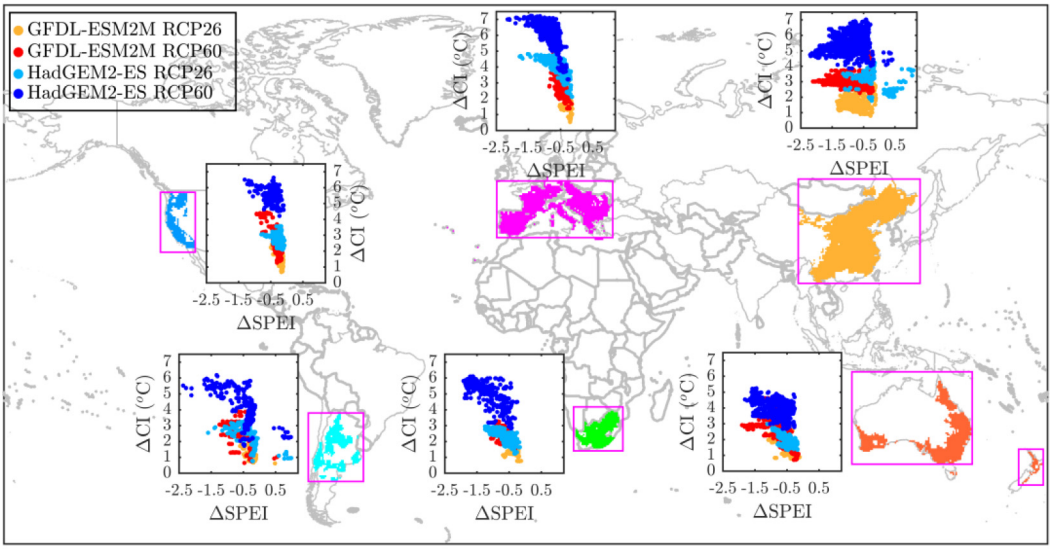


Fig. 5. Boxplots of the changes in the climatic indices under the four considered climate change scenarios in 2099 with respect to the climate in 1950.

(a) Huglin Index against Cool Night Index



(b) Cool Night Index against SPE Index



(c) Huglin Index against SPE Index

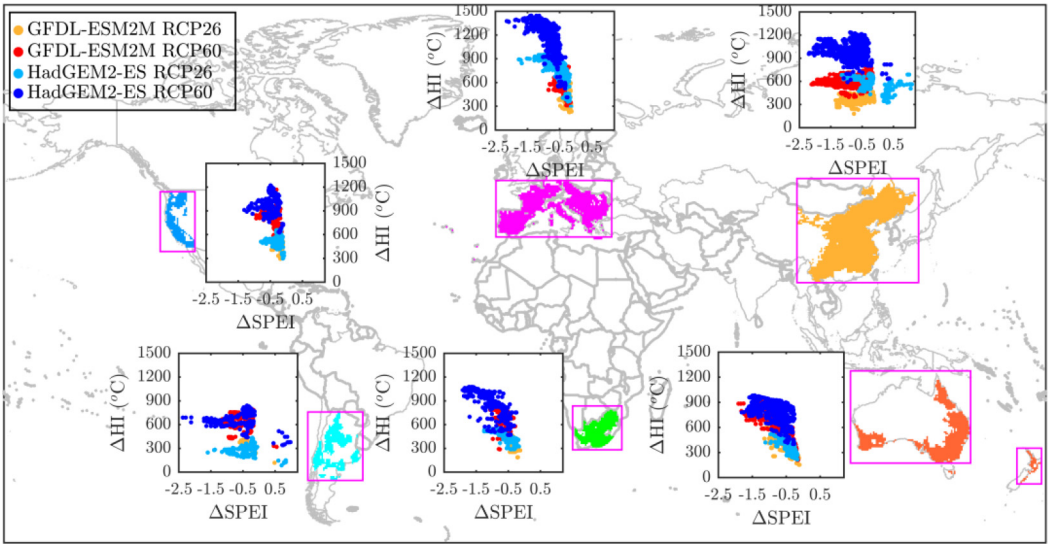


Fig. 6. Changes in one index against the change in other index for the six studied wine-producing regions and the four outputs of the GCM simulations. (a) The Huglin Index against the Cool Night Index. (b) The Cool Night Index against the SPE Index. (c) The Huglin Index against the SPE Index.

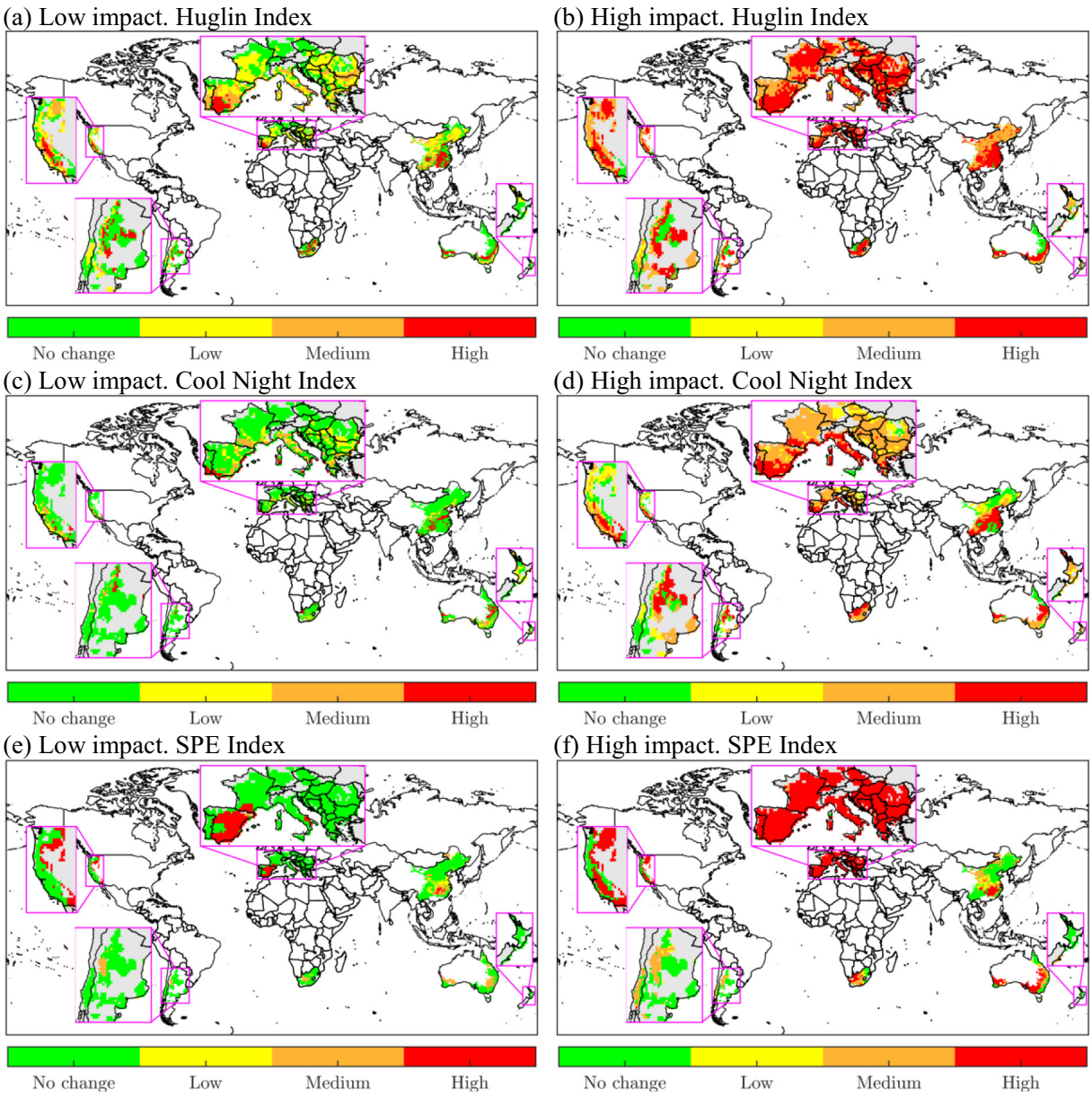


Fig. 7. Adaptation efforts as result of the estimated changes in indices. Adaptation efforts are ranked low in yellow, medium in orange, and high in red. No change is plotted in green. We plot in the left column the adaptation efforts for the GCM simulation that results into the lower changes in the indices, the GFDL-ESMSM GCM driven by the RCP2.6, and in the right column the efforts for the GCM simulation that provides the higher changes in indices, the HadGEM2-ES GCM driven by the RCP6. We plot the needs for the Huglin Index in the first row, the Cool Night Index in the second one and the SPE Index in the third one.

3.4. Regional adaptation needs

We assign index thresholds to represent suitability ranges based on the literature estimates. Category names and corresponding thresholds for the Huglin and Cool Night indices are those proposed by Tonietto and Carbonneau (2004), and for the SPE Index by McKee et al. (1993) and Hayes et al. (1999). For each climatic indicator, we define three levels of adaptation needs (low, medium and high) based on the change of the index within uncertainty thresholds from the current to the projected climate, following Tonietto and Carbonneau (2004). The results obtained (Fig. 7) are of interest for developing policies that may drive climate change adaptation, and increase the comprehension of the effect and the uncertainty of projections.

The adaptation efforts for the six regions are ranked low, medium and high, and no change for those cells where without change in index classification (Table 3). We include the adaption needs for two climate change scenarios: the low impact and the high impact. The low impact scenario corresponds to the projections with the lowest temperature increment and rainfall decrease, and will produce the lowest changes in the agro-climatic indicators at global scale. In our study, this scenario corresponds to the projection of the GFDL-ESMSM GCM driven by the RCP2.6. The high impact scenario is the projection with the highest increase in temperature and decrease in rainfall. It will generate the highest changes in the indicator. In our study it corresponds to the projection of the HadGEM2-ES GCM driven by the RCP6.0. We assess the climate indicators individually, since it allows us to provide a more comprehensive effect of the climate drivers on the grapevine production. We are aware that the interaction between climate indicators may result in larger adaptation effort than when these are assessed individually for each index.

We consider low adaptation effort due to the change in the Huglin Index those areas where the indicator changes from cool to temperate or temperate-warm, since warmer growing seasons and less frequent frost events could decline constraints to ripen of all grape varieties.

Instead, adaptation efforts are considered to be medium or high in those areas where the Huglin Index is expected to change to warm or very warm (see Table 3). Temperature increases may exceed the optimal temperature limits to ripen the grapevines.

Regarding the Cool Night Index, areas where the indicator shifts to cool are considered to need low adaptation effort, to temperate with medium adaptation effort, and to warm with high effort. Warmer night temperatures during the growing season may involve a loss of quality, in terms of loss of aroma and color (Table 3).

Moderate shift decreases in the SPE Index may involve a moderate water stress which may increase quality (van Leeuwen et al., 2004). Consequently, low adaptation needs are expected in those areas where the indicator evolves from humid to sub-humid or moderately dry, or from sub-humid to moderately dry, since irrigation will be necessary only in certain times (Table 3). Areas where the index may evolve towards dryer conditions in the future are expected to require medium or high adaptation needs, as irrigation may become mandatory to increase quality or yield due to the frequent stress events.

Climate predictions show large uncertainties in temperature and precipitation projections, and consequently, large uncertainties in adaptation needs. In the following paragraphs, we analyze the regional implications of the shifts in indices for two climate change scenarios whose outputs may involve low impact and high impact respectively.

3.4.1. North America

The low impact climate scenario projects low or non-existent adaptation needs due to the shift in Huglin Index in most of the areas of North America. Needs are medium in the Snake River Plain (south of Idaho), and the Columbia Valley, but high in the Central Valley (California). In contrast, the adaptation needs projected by the high impact climate scenario are medium in most of the areas, except in the Columbia Basin and the Central Valleys, where they are high, and the Imperial Valley, where they are non-existent because the index is currently within the very warm threshold.

Regarding the Cool Night Index, adaptation needs are non-existent for the low impact climate scenario projections, with the exception of some specific areas in the south of the Central Valley where the needs are low, medium or even high. The high impact climate scenario shows a tendency towards low adaptation needs in the north of the region – Willamette and Columbia valleys and the Snake River Plain – and medium needs in the south part, except the Central Valley where they are high.

The adaptation needs due to the shift in the SPE Index are non-existent for the low impact climate scenario projections, except some specific areas in the border of the Snake River Plain with high needs. Nevertheless, the adaptation effort would be high in the whole Columbia Valley, Snake River Plain and the Central Valley for the high impact climate scenario, and non-existent for the remaining areas.

The projected warming shifts may reduce constrains to ripen more varieties, especially in the northern vineyards, and enable the farming in areas that currently are cold. Adaptation may need more attention in the warmer areas, the Central and Imperial valleys, where night temperatures during ripening could reach upper optimal values. However, in the cooler areas, warming could have a positive effect thanks to the reduction of frost events favouring optimal ripening, especially under the high impact scenario. The projected increases in the Cool Night Index indicate that negative effects may be avoided by oenological techniques or wine management practices to adjust ripening. Water availability would be in the future a limiting factor in the Central Valley, where irrigation needs may increase. However, the reduction of precipitation in the northern areas could increase quality, and humidity-nurtured diseases may be reduced.

3.4.2. Europe

Shifts in the Huglin Index provided by the low impact climate scenario are expected to require low or non-existent adaptation efforts. Medium efforts may be necessary in the south of the Iberian Peninsula, the Po valley in the north of Italy, and the border between Romania and Bulgaria — the Danube valley. Efforts could become high in the south of Spain. The high impact scenario projects high adaptation efforts in most of Europe, and medium efforts in the north of the Iberian Peninsula, the south of France and isolated areas across the continent.

The adaptation needs due to the change in the Cool Night Index projected by the low impact scenario are non-existent or low in most of the European areas. Nevertheless, high needs are detected in certain areas of the south coast of the Iberian Peninsula and Sardinia and medium efforts across small areas of the southeast Spain, north of the French Pyrenees, Italy – Po Valley – and Greece. The high impact scenario projects medium adaptation needs in most of Europe, except some areas in Germany and Bulgaria with medium or non-existent efforts, and the south of the Iberian Peninsula, Sardinia and most of Italy where high effects are expected.

The low impact scenario projects non-existent adaptation needs due to the shift in the SPE index in most areas of Europe, except in the central-west part of the Iberian Peninsula and the central-south of France where high efforts are expected. Nevertheless, high efforts are provided by the high impact scenario in all areas of Europe.

Temperature shifts may have positive effects in northern Europe, due to frost reduction and optimal night temperatures during ripening period, and may enable vine-growing in areas currently too cold. Nevertheless, warmer locations or early varieties in southern Europe are likely to reach or exceed upper temperature thresholds, with especial intensity in the Mediterranean region under the high impact scenario, involving higher wine color and aromas potential reduction. Thus, medium and high adaptation efforts may be needed at all levels, ranging from easy wine-making techniques to more strong actions like growing later varieties and high trellis or rootstocks changes. Irrigation may become mandatory in southern Europe, and irrigated areas may extent to northern Europe under the high impact scenario; whereas the decrease of precipitation in northern Europe may increase quality and reduce humidity-nurtured diseases.

3.4.3. China

Trends in the Huglin Index projected by the low impact climate scenario may require none or low adaptation effort in most areas of China, except in the Middle Yangtze Plain and some areas in the Lower Yangtze Plain, the Sichuan basin and the Yun-Gui Plateau where high or middle efforts may be needed. Under the high impact scenario, the required adaptation efforts would become medium and high. The most affected areas would be the North-China plain, the Lower Yangtze Plain, the Sichuan Basin and the south of the Yun-Gui Plateau.

Regarding the adaptation needs due to shifts in the Cool Night Index under the low impact scenario, most of the areas of China would not require adaptation. Some areas in the North-China Plain and the Sichuan Basin may need high efforts. Nevertheless, the required efforts under the high impact scenario become medium or high in the whole North-China Plain, the lower and middle Yangtze Plain, the Yung-Gui Plateau and some areas in the south of the Manchurian Plain.

Shifts in the SPE Index under the low impact scenario would demand medium or even high adaptation needs in the Gan and Xiang Valleys, and low in some areas of the middle and lower Yangtze Plain. The remaining areas of China would not need adaptation. Under the high impact scenario, efforts became high in the whole Gan and Xiang Valleys, and medium in some areas of the Loess and Inner Mongolia Plateaus.

The projected changes in temperatures may have positive consequences in vineyards located in northern China – Manchurian Plain, Inner Mongolia and Loess Plateaus – as a result of frost events reduction and warmer ripening periods. But projections show increments of heat stress in warmer areas, such as North-China and Yangtze Plains or Yun-Gui Plateau, and adaptation responses may be needed. Adaptation measures may vary from new vine management to adjust ripening in those areas with moderate changes to the introduction of later varieties or

rootstocks changes in areas with high temperature changes, depending on the changes projected by the scenarios. Shift in the SPE Index indicate that irrigation may be needed in areas of the Gan and Xiang Valleys.

3.4.4. South America

The expected adaptation efforts due to the change in the Huglin Index under the low impact scenario are non-existent or low in most of South America, except certain areas of La Plata Basin in Argentina. The high impact scenario predicts medium or high efforts in most areas, with the exception of some areas of the upper La Plata Basin where no needs are expected since the index is currently within the very warm threshold.

The shifts in the Cool Night Index would not require adaptation for the low impact scenario. Nevertheless, adaptation needs are much higher under the high impact scenario. Efforts may be high in most areas of the Upper La Plata basin and medium in the La Plata and Rio Negro mouths.

Regarding the SPE Index, the low impact scenario projects no adaptation needs, with the exception of the Cordoba Mountain area where medium efforts are expected. The areas with medium adaptation needs may extend wider for the high impact scenario. These could extend to the Upper La Plata Basin and most areas in Chile.

Warming in areas of northern Argentina, as for instance Upper La Plata Basin, might exceed optimum ripen temperatures for some grape varieties that could reduce grape quality, but only under the high impact scenario. In cooler regions, the shift in temperatures may involve positive effects thanks to the reduction of frost events, and quality could increase due to more adequate ripening conditions. Irrigation may not be necessary, and the reduction of precipitation may increase quality due to moderate water stress during ripening periods.

3.4.5. South Africa

The adaptation effort due to the shift in the Huglin Index may be non-existent or low in a large part of the country for the low impact scenario. Medium and high efforts may be needed along some areas of the Vaal Basin, the north of the Great Karoo, and the Limpopo lowlands. Most of the areas would require high adaptation needs under the high impact scenario. The effort would be medium in some areas of the Eastern midlands and inexistent in the Kalahari Desert, since the index is currently within the very warm threshold.

The shift in the Cool Night Index under the low impact scenario would not require adaptation in most of the country. Nevertheless, the high impact scenario project medium adaptation effort in the south part of the country, from the Orange and Vaal rivers to the coast, and high needs in the north part.

The change in the SPE Index under the low impact scenario would not demand adaptation efforts in most of the territory, except in the Kaap Plateau where medium effort may be needed. Efforts under the high impact scenario are more demanding. No or low effort may be needed in the Limpopo lowlands and the upper Vaal Basin. Medium efforts are required in the Great Karoo Land and the south part of the lower Vaan Basin and high efforts in the Kalahari Desert and the Kaap Plateau.

Special attention may require the northern areas of South Africa – Orange and Vaal Basins, Kalahari Desert and Kaap Plateau – where projections with the high impact scenario indicates that the quality of the wine may be reduced due to the high night temperatures during the ripening period. Negative effects may be avoided with farming practices in the short term up to grape-variety changes or locations in the long term. The high impact scenario projects that some areas close to the cost may require relatively easy measures for maintaining grape quality, as for instance easy oenological techniques or farming practices, but adaptation needs disappear under the low impact scenario. Nevertheless, shifts in temperature could have positive effects in areas close to the coast, due to a reduction of frost events. Irrigation may be necessary in the whole country, except in the Limpopo Lowlands.

3.4.6. Oceania

The change in the Huglin Index under the low impact scenario may involve in some areas with high adaptation effort in the inland of the Margaret Valley in the Western Australia Territory and in the inland vineyards of the Victoria and South Wales Territories. The high impact scenario would extend the previous areas towards the inland territories, as well as the coast, and New Zealand.

Under the low impact scenario, the changes in the Night Cool Index would require high and medium efforts in certain areas of the northwest part of the Margaret Valley, as well as some vast inland areas of Queensland, South Wales, and Victoria Territories. The high impact scenario may involve strong and medium efforts in the whole vineyards of Australia, except in the Cape York Peninsula where no adaptation is needed, and medium efforts in New Zealand.

The trend in the SPE Index under the low impact scenario would lead to medium adaptation efforts in the inland territories of Western Australia, Victoria, and South Wales, whereas no adaptation needs are projected in the remaining areas of Oceania. The high impact scenario would increase the efforts to high and medium in the inland areas of all Australian territories.

Adaptation measures may require more attention in the warmer southern territories, where grapevines may be exposed to excessive warm growing seasons, and therefore a quality loss. Strong adaptation efforts may be required under the high impact scenario, as currently these areas are warm. Irrigation may become mandatory in the southern territories, whereas the reduction in precipitation could have positive consequences in the northern territories, such as Queensland, due to moderate water stresses during the growing season and the reduction of humidity diseases.

4. Conclusions

We have analyzed how climate change may transform vineyards. We have estimated changes in three bioclimatic indices (a drought indicator and two thermal ones) from the climate in 1950 to the scenario in 2099. The drought indicator provides insights to prepare adaptation for extreme events in probabilistic terms. The temperature indicators provide information on the transition towards suitable zones of production. Future projections suggest a lack of water to maintain current levels of production in all regions of the world. Moreover, thermal suitability of grapevine might be greatly affected in China and the Mediterranean region. Nevertheless, the possibility of quality wines is not altered within the regions with adequate suitability.

Grape producers and wine industry use many strategies to adapt to their environment, as for instance, irrigation, rootstocks changes, oenological techniques, new vine management practices or even introduction of new grape varieties. However, there is a range of barriers and incentives to carry out the necessary transformation of grapevine production regions in view of climate change. In some situations, producers and industry undertake no adaptation due to the perception that adaptation is not critical or due to lack of resources. In other situations, policies drive adaptation; but in others, policies may represent barriers (Resco et al., 2016).

The predominant approach presented in this paper is to evaluate the effect of several climate scenarios in variables that affect grape growing. Several features of our analysis have been already recognized elsewhere by previous studies. Our conceptual framework combines elements from several fields – climate change, climatic variability, agronomy and policy – with a consistent methodology uniformly applied worldwide. Our methodology contributes to analyze the relative magnitude of adaptation needs at the global scale. The analysis presented here is intended to guide more empirical studies at the local level, providing a magnitude of the adaptation effort; as well as more policy oriented studies at the global level, thanks to uniform metrics on adaptation needs. It should be noted that best practices and adaptation measures against climate change has been conducted and tested at local scale.

Some of them are promoted and supported by governments, as for instance the Common Agricultural Policy in the European Union. Moreover, some wine regions promote climate adaptation practices within the frame of sustainable wine production programmes. Some examples are the California Sustainable Winegrowing Alliance in USA (Zucca et al., 2009), or the VIVA project in Italy (Lamastra et al., 2014, 2016), which promote sustainable practices, including those for adapting to climate change.

The perspectives of the adaptation needs would then have to be completed by local investigations to provide information on how winegrowers and wine industries are anticipating or not to climate changes and their adaptation needs. It is clear that global and national policies will not be locally efficient to solve adaptation needs.

A multitude of solutions are available that can anticipate climate change damage to grape growing regions. However, the success depends on transforming the current model of production. Challenges and limitation to implement adaptation strategies could be understood by an additional study on how to support the adoption of agricultural innovation. The transfer of knowledge may play a key role on this study. Many of the greatest barriers to adoption are beyond the producer and even the industry. Moreover, in many cases, only the transformations that are supported by institutions will be effective.

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Appendix A. Data climatic scenarios

Historical and future climatic scenario data used in this research were provided by the Inter-Sectoral Impact Model Intercomparison Project phase 2b (https://www.isimip.org/). Data are bias-corrected with worldwide 0.5° × 0.5° spatial resolution and daily temporal resolution.

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